<heading>INTRODUCTION</heading>In this report, a torque sensor was designed. It was a shaft-type cantilever, which was clamped to a frame at one end, with the other end left free to be twisted under a torque. This torque was applied via a thin steel bar attached to the free end of the shaft, and a force applied to the other end of the steel bar. The shaft was a hollow one, made of steel with the dimensions as follows: length L = 200mm; outside diameter d 0 = 20mm and the internal diameter d i = 17mm. Once this test-rig was set up, it had been proposed that the rig was instrumented so that an automatic measurement of the torsion could be given. Diagrams of the test rig were shown below. <figure/><figure/><heading>METHOD</heading>To give this automatic read out of the torsion, it was decided that a torque cell should be implemented. A torque cell was a transducer and transducers were devices used for the measurement of a physical quantity by electrical means, i.e. used to convert non-electrical measurands into electrical quantities. They were used because this method often assisted subsequent operations on the data. In this case, the torque cell was converted an applied torque into an electrical output signal. A torque cell contained a mechanical element- the circular shaft, and a sensor- strain gauges. Firstly the type of strain gauges was chosen. In fact there were two types of gauges, metal or semiconductor. The metal gauges were in the form of a flat coil of wire or etched metal foil and the semiconductor gauges were a strip of semiconductor material in-between two connection leads. The element was wafer-like and had an insulating backing material so that it could be stuck like a postage stamp onto surfaces, using a suitable adhesive. Strain gauges worked on the principal that: FORMULA where <list> R = resistance, = resistivity, L = length, and A = area of the element.</list>So when the element was stretched, its length increased, its cross-sectional area decreased, and there was also a change in its resistivity. The result was that the resistance of the element changes. Generally, the semiconductor strain gauges were made from silicon and they had a much higher gauge factors than the metal ones which made them much more sensitive than the metal ones (Gauge factors were between 100 - 175 or -100 to -140 depending on whether the silicon was doped with 'P' or 'N' type material, compared with gauge factors of 2 for the metal ones), but it didn't mean that they were automatically better than the metal ones though. The strain gauges based on semiconductor materials were rather more expensive, more difficult to apply and had greater sensitivity to temperature changes than the metal ones. The greater sensitivity to temperature changes meant that the relative change in resistance is now non-linear and therefore more complicated. Due to these negative points, the metal foil strain gauges were chosen. Four active strain gauges are used in order to obtain maximum possible bridge output voltages, to provide temperature compensation, and to make the sensor/transducer insensitive to forces and moments other than the one being measured. These are mounted on two perpendicular 45 helices that are diametrically opposite to one another. Gauges 1 and 3, are mounted on the right hand helix, and sense a positive strain (tension), and gauges 2 and 4, mounted on the left-hand helix, sense a negative strain (compression). The two 45 helices define the principal stress and strain directions for a circular shaft subject to pure torsion. This set-up described can be seen in the following diagram <figure/>The torque, T transmitted by a shaft is related to the maximum shear stress, produced on the shaft surface by the equation: FORMULA where J is the polar second moment of area of the shaft section and r the radius of the shaft. For a hollow circular shaft J = (d 04 - d i4)/2, where d 0 is the outside diameter of the shaft and d i is the internal diameter of the shaft. Thus the maximum shear stress is: FORMULA The above set-up of the strain gauges therefore would be able to sense, and thus provide us with the information of the shearing stresses on the shaft. It can be seen from the above diagram how the strain gauges will be set up. We already know that when strain gauges are put under a strain that their resistance changes. Thus, we need a circuit that will convert a change in resistance into an output voltage. A circuit commonly used for this purpose is a Wheatstone bridge circuit. (Shown below) <figure/>As can be seen from the diagram previous, the output voltage, V 0 of the bridge can be determined by treating the top and bottom parts of the bridge as individual voltage dividers. Thus, FORMULA FORMULA The output voltage V 0 of the bridge is: FORMULA Where R 1 = gauge 1 etc. The above equation indicates that the initial output voltage, V 0 = 0 if FORMULA This means that the bridge is balanced. The ability to do this makes it considerably easier to measure small changes in voltage output, V 0. We are using a circuit with four active bridges. Providing that they are correctly connected into the bridge, so that one opposite pair (e.g. R 1, R 2) are in tension and the other opposite pair (e.g. R 3, R 4) are in compression; then the sensitivity is four times that of a single element gauge. This bridge also compensates for changes in gauge resistance due to temperature. For metal gauges the effect of temperature is to multiply each gauge resistance by the factor 1 + T; which cancels out in the above voltage equation, as those gauges in tension will have their resistance increased by a temperature change and those in compression will have theirs decreased. As; FORMULA and; FORMULA FORMULA FORMULA FORMULA Also: FORMULA FORMULA Where G = Gauge factor, or strain sensitivity and = strain then; FORMULA FORMULA FORMULA This shows that there is a linear variation between the output and the variation of resistance of the strain gauges. <heading>a)</heading>It was shown earlier that there is a relationship between the maximum shear stress, on the surface of the shaft and the torque, T in the system, given by the following equation: FORMULA Where J is the polar second moment of area of the system and r is the outside radius of the shaft. This can be rearranged into the following form using J = (d 04 - d i4)/2 for a hollow circular shaft: FORMULA <heading>b)</heading>Now the relationship between the strain and the shear stress will be looked at. For a circular shaft subject to pure torsion, the direction of the maximum stresses resulting from this shear are at 45 to the shaft axis. This can be seen from looking at the diagram earlier showing the set-up of the strain gauges and the following equation: FORMULA These stresses at right angles to each other will give rise to strains in these directions of: FORMULA and FORMULA where E is Young's modulus for the material and Poisson's ratio, which is given by = -T/L which are the transverse and longitudinal strains. These strains can be measured by the use of the resistive strain gauges aligned as shown in the earlier diagram. <heading>c)</heading>When looking at the relationship between the resistance and the strain for each gauge, we can start with the following equation that: FORMULA Thus the fractional changes in resistance of each of the strain gauges is: FORMULA or FORMULA <heading>d)</heading>When looking at the relationship between the bridge output and the torque we go back to the simple equations first. To balance the circuit R 1R 4 = R 2R 3 so that V 0, which is the potential between B and D on the earlier diagram of the circuit, is zero. So when there is a change in the resistance of R 1 then FORMULA Similarly, the potential difference across R 4 is: FORMULA Thus the potential difference between B and D is: FORMULA This is a balanced condition again. Also: FORMULA When a force is applied to the shaft, each of the resistors will change their resistance. The changes in resistance in relation to the denominator terms where we have the sum of the resistances is insignificant and can be neglected. Thus: FORMULA FORMULA We also know that: FORMULA when balanced there is no change in output voltage so: FORMULA And; FORMULA therefore; FORMULA FORMULA Hence, the output voltage V 0 from the bridge is proportional to the torque T acting on the shaft. The sensitivity of the torque cell depends on the diameter of the shaft (d o), the shaft material (E and ), the gauge factor (G), and the voltage applied to the Wheatstone bridge (V S). The range of the torque cell depends on the diameter of the shaft and the proportional limit of the material in torsion. We need now though to amplify the output signal of the circuit as the strain gauges in the circuit will only be changing their resistance by a small amount, so the output voltage will therefore only change by a small amount too. Also we need to consider the fact that when we amplify the signal, we will also amplify any noise in the signal, so a filter needs to be employed to attenuate the noise in the signal before amplification. To do this we will use an active filter. This is a device that will combine an operational amplifier and an RC filter. We chose to use a non-inverting op amp as this will amplify the signal and will give a positive value for a positive torque. A diagram of a non-inverting op amp is shown below: <figure/>The two resistors in the above circuit can be used to calculate the gain of the circuit (G C). The formula that is used to do this is as follows: FORMULA FORMULA where G is the gain of the amplifier. This will be combined with a low-pass RC filter in order to attenuate the noise in the signal. Electrical noise can be a problem as the output voltage from the Wheatstone bridge circuit is only a few millivolts. The electrical noise occurs as a result of magnetic fields generated by current flow in wires in close proximity to the lead wires or bridge, which induce voltage (noise) in the signal loop. This combination of op amp and filter is called an active filter. Active filters are used where select frequencies can be attenuated and the signal amplified during the filtering process. Shown below is an active filter with a non-inverting op amp and a low-pass filter: <figure/>Now all that is needed is to employ this into the circuit and combine it with the Wheatstone bridge circuit. Taking the output signal from the Wheatstone bridge circuit and using it as the input signal for the active filter does this, as this is the signal that needs to be amplified. The combined circuit is shown below: <figure/>The circuit has now been set up with strain gauges to sense the stresses in the shaft, and these mechanical outputs have been converted into electrical ones and amplified to a sufficiently high level with the noise attenuated so the signal can be read by a voltage-measuring instrument. This system now needs to be able to be read and calibrated for data presentation. To calibrate this system, we need to precisely measure R 1, R 2, R 3, R 4, V S; the gain G of the amplifier; and the sensitivity S R of the recorder (i.e. the voltmeter). The system calibration constant C for the entire system is then given by: FORMULA Where, S A = the amplifier sensitivity, and S R = the recorder sensitivity (volts per division) The strain recorded with the system is given in terms of the system calibration constant as: FORMULA where, d S = the deflection of the recorder in divisions.